Development of A Tsunami Forecast Model for Key West, Florida

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Abstract

Forecast and high-resolution reference models were developed for Key West, Florida in support of the Short Term Inundation Forecast application for Tsunamis system built for the NOAAs Tsunami Warning Centers. A comparison study was also conducted for the forecast and high-resolution models using synthetic mega and micro tsunami events to test for stability. Both forecast and high-resolution reference models were also calibrated to a historical reconstruction of the 1755 Lisbon event. The results of the modeling show relatively little impact for all basin wide subduction generated tele-tsunami event. Results of stability tests showed that the model was stable for the entire range of Tsunami events (up to 9.3 Mw).

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1 Background and Objectives

The National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami, Research (NCTR) at the NOAA Pacific Marine Environmental Laboratory (PMEL) has developed a tsunami forecasting capability for operational use by NOAAs two Tsunami Warning Centers located in Hawaii and Alaska [12]. The system is designed to efficiently provide basin-wide warnings of approaching tsunami waves accurately and quickly. The system, known as the Short-term Inundation Forecast of Tsunamis (SIFT), combines real-time tsunami event data with numerical models to produce estimates of tsunami wave arrival times and amplitudes at a coastal community of interest. The SIFT system integrates several key components:

- Deep-ocean observations of tsunamis in real time;
- A basin-wide pre-computed propagation database of water level and flow velocities based on potential seismic unit sources;
- An inversion algorithm to refine the tsunami source based on deep-ocean observations during an event; and
- High-resolution tsunami forecast models.

The objective of forecast model development is to provide real-time tsunami predictions for selected coastal locations while the tsunami is propagating through the open ocean. Forecast models will be incorporated into the U.S. tsunami warning system for use at the Pacific and West Coast-Alaska Tsunami Warning Center. Synolakis et al. (2007) [9] and Tang et al. (2008) [11] describe the technical aspects of forecast model development, stability testing and robustness.

Due to its remote location, low-lying population center, and high influx of seasonal tourists, the potential impact of a tsunami event on the economy and infrastructure of Key West is high. To manage this risk, the Tsunami Warning Centers have designated Key West as a community that would benefit from a Tsunami forecast model. The report describes the development and testing of the Key West forecast model including the data set up, calibration with historical events, and stability testing using synthetic events to validate previous results.

2 Forecast Methodology

A high-resolution inundation model was used as the basis for development of a tsunami forecast model to operationally provide an estimate of wave arrival time, wave height, and inundation at Key West following tsunami generation. All tsunami forecast models run in real time while a tsunami is propagating across the open ocean. The Key West model was designed and tested to perform under stringent time constraints given that time is generally the single limiting factor in saving lives and property. The goal of this work is to maximize the length of time that the community of Key West has to react to a tsunami threat by providing accurate information quickly to emergency managers and other officials responsible for the community and infrastructure.

The general tsunami forecast model, based on the Method of Splitting Tsunami (MOST), is used in the tsunami inundation and forecasting system to provide real-time tsunami forecasts at selected coastal communities. The model runs in minutes while employing high-resolution grids constructed by the National Geophysical Data Center. The Method of Splitting Tsunami (MOST) is a suite of numerical simulation codes capable of simulating three processes of tsunami evolution: earthquake, transoceanic propagation, and inundation of dry land. The MOST model has been extensively tested against a number of laboratory experiments and benchmarks [8] and was successfully used for simulations of many historical tsunami events. The main objective of a forecast model is to provide an accurate, yet rapid, estimate of wave arrival time, wave height, and inundation in the minutes following a tsunami event. Titov and Gonzlez (1997) [13]. describe the technical aspects of forecast model development, stability, testing, and robustness, Tang et al., 2009 [10] provide detailed forecast methodology

A basin-wide database of pre-computed water elevations and flow velocities for unit sources covering worldwide subduction zones has been generated to expedite forecasts [7]. As the tsunami wave propagates across the ocean and successively reaches tsunameter observation sites, recorded sea level is ingested into the tsunami forecast application in near real-time and incorporated into an inversion algorithm to produce an improved estimate of the tsunami source. A linear combination of the pre-computed database is then performed based on this tsunami source, now reflecting the transfer of energy to the fluid body, to produce synthetic boundary conditions of water elevation and flow velocities to initiate the forecast model computation.

Accurate forecasting of the tsunami impact on a coastal community largely relies on the accuracies of bathymetry and topography and the numerical computation. The high spatial and temporal grid resolution necessary for modeling accuracy poses a challenge in the run-time requirement for real-time forecasts. Each forecast model consists of three telescoped grids with increasing spatial resolution in the finest grid, and temporal resolution for simulation of wave inundation onto dry land. The forecast model utilizes the most recent bathymetry and topography available to reproduce the correct wave dynamics during the inundation computation. Forecast models, including the Key West model, are constructed for at-risk populous coastal communities in the Pacific and Atlantic Oceans. Previous and present development of forecast models in the Pacific [12] [15] [11] [16] have validated the accuracy and efficiency of each forecast model currently implemented in the real-time tsunami forecast system. Models are tested when the opportunity arises and are used for scientific research. Tang et al., 2009 [10] provide forecast methodology details.

3 Model Development

The general methodology for modeling at-risk coastal communities is to develop a set of three nested grids, referred to as A, B, and C-grids, each of which becomes successively finer in resolution as they telescope into the population and economic center of interest. The offshore area (A-grid) is covered by the largest and lowest resolution while the near-shore details (C-grid) are resolved to the finest scale to the point that tide gauge observations recorded during historical tsunamis are resolved within expected accuracy limits. The procedure is to begin development with large spatial extent merged bathymetric topographic grids at high resolution, and then optimize these grids by sub sampling to coarsen the resolution and shrink the overall grid dimensions to achieve a 4 to 10 hour simulation of modeled tsunami waves within the required time period of 10 minutes of wall-clock time. The basis for these grids is a high-resolution digital elevation model constructed by the National Geophysical Data Center (NGDC) using all available bathymetric, topographic, and shoreline data to reproduce the wave dynamics during the inundation computation for an at-risk community. For each community, data are compiled from a variety of sources to produce a digital elevation model referenced to Mean High Water in the vertical and to the World Geodetic System 1984 in the horizontal (http://ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html). From these digital elevation models, a set of three high-resolution, reference elevation grids are constructed for development of a high-resolution reference model from which an optimized model is constructed to run in an operationally specified period of time. This operationally developed model is referred to as the forecast model.

Development of an optimized tsunami forecast model for Key West began with the spatial extent merged bathymetric/topographic grids shown in Figure 2. Grid dimension extension and additional information were updated as needed and appropriate. A signicant portion of the modeled tsunami waves, typically 4 to 10 hr of modeled tsunami time, pass through the model domain without appreciable signal degradation. Table 3 provides specific details of both reference and tsunami forecast model grids, including extents and complete input parameter information for the model runs is provided in Appendix A.

3.1 Forecast Area

Key West is located at the southern most tip of an archipelago of low-land islands in southern Florida known as the Keys. The Keys are a chain of oolite and limestone islands formed during the last ice age when sea levels dropped and fossilized ancient coral reefs. Key West is sighted 129 miles Southwest of Miami and is the southernmost point of the continental United States. Known as the Gibralter of the West, Key West has always held a strategic interest for the United States. The U.S. Military maintains strong presence in Key West and today occupies 3000 acres, including a Naval Air Station, Coast Guard Facilities, and Surface Warship piers. Historically specializing in fishing and wreck salvaging, the city of Key West has long been one of the most prosperous cities in Florida. Its relative isolation, ideal climate, and setting have fostered a unique culture. Tourism continues to be a vitally important part of the Key West economy. In 2011 alone, over 1.2 million tourists visiting Key-West and $1.1 billion was spent spent on tourism and recreation [5].The city of Key West is the county seat of Monroe County and encompasses the island of Key West, a portion of Stock Island, Sigsbee Park, Fleming Key, and Sunset Key. The city comprises a total area of 7.4 square miles, of which 5.6 square miles is land approximately half of which is fill - with a maximum elevation of 18 feet. The 2010 Census reported 24,649 people and 8925 households residing in the town [1]. The deepest charted depths in the approaches to Key West are 194 meters. The continental shelf extend east 5-8 kilometer offshore [4]

3.2 Historical Events and Data

Very little tsunami data exists in the tide-gauge record for Key West and the surrounding islands. There exists evidence of landslide driven paleo-tsunamis in the Gulf of Mexico [6], however that topic is outside the scope of this paper. Without a strong historical record, the Forecast Model and Reference Models had to be calibrated against each other. Additional data points in the tsunami record would significantly aid in validating the model. When additional tide gauge records become available the model should be re-verified at the earliest possibility opportunity. A re-construction of the 1755 Lisbon event was synthesized for this report.

There is an NOS water level gauge (see Figure 3) in the naval basin on the west side of Key West island. The GPS verified location of the gauge is 24 33.3 N and 81 48.4 W. The mean tidal range in Key West is 1.28 ft, with a diurnal range of 1.81 ft. The mean sea level is 5.45 ft. Additionally, as can be seen in Figure 2, synthetic tide gauges were places around Key West. Table 3 describes the geographic location of each gauge.

3.3 Model Setup

Figure 2 show the extent of the Forecast and Reference model grids respectively. The extent of the grids can be seen in Table 3. The high resolution Key West reference model consists of three nested grids and were chosen with a higher bathymetric resolution than forecast model grids to capture potential inter island reflections and channel effects. Generally, the outermost, or A grid, encompasses the entire Florida Keys out to the coastal shelf with 30-arc-second resolution. The intermediate, or B, grid encompasses the Marquesas Keys to Big Pine Key with 3-arc-second resolution. The innermost, or C grid, encompasses township of Key West including the airport and Naval Air Station with 1/3-arc-second resolution. NGDC bathymetric and topographic data were used for the source inputs for all reference model grids. Iterative and localized Butterworth smoothing was performed on the A, B, and C high resolution reference model grids to remove identified high frequency noise. This smoothing was minimal and did not impact the results of successive model runs. The Key West tsunami forecast model was optimized to decrease the computation time necessary to provide real-time inundation and current forecasting for the protection of life and property. The A, B, and C forecast grids were created by subsampling the high resolution reference grids as can be seen from Table 3. Comparisons of the forecast model and reference model results can be seen in Figures 5-18 for a variety of tide stations and scenarios. A reference model simulation of 4 hours requires 668.48 minutes of computation, whereas the optimized forecast model reduces the computation time of a 4 hour simulation to 8.55 minutes of wall-clock time; nearly an 80 fold increase in efficiency.

4 Results

A list of recreated historic and synthetic tsunamis can be seen in Tables 1 and 4. Tsunamis were measured from the Key West tide station. A maximum 2.63 meter high wave was observed in the C grid. This maximum wave was the result of the Nicaraguan ATSZ 68-77 event. Synthetic scenarios were also used to test the stability of the Key West tsunami forecast model and to conduct a hazard assessment.

4.1 Model Validation

DART system observations have played a critical role in defining the tsunami source and have provided accurate real-time tsunami forecasts for U.S. coast-lines since the array was tested in the 1990s and modernized in 2001. Previous studies have shown successful applications of NOAAs experimental tsunami forecast system that constrains the tsunami source from the real-time tsunameter measurements, which is subsequently used to provide real-time propagation and coastal inundation forecasts [14] [16] [10] [15]. These real-time inversions of the tsunami source have shown a forecast accuracy of up to 90% of the tsunami waveforms at distant coastlines [16]. Fortunately for the residents of Key West, but unfortunately for Tsunami researchers, there exists very little Tsunami data in the Key West tidal record. Figure 3 shows the geographical epicenter of the 1755 Lisbon event used in the model validations. A summary of this event can be seen in Table 2. Figure 9 shows the computed Forecast and Reference model time series at the NOS tide station. There is a strong correlation between computed results. The Reference model is nearly identical to the Forecast model in wave amplitude, period, and phase. Differences between the Reference and Forecast models can be seen in later waves, but this is usually limited to differences in higher frequency wave components and should be expected as local and high-resolution effects become more dominant. Excluding higher order error terms, the Key West Forecast model substantively represents the Reference model while saving significant computational effort.

4.2 Model Stability and Testing Using Synthetic Scenarios

Figure 4 shows the geographical epicenters of the synthetic tsunamis used in the model calibrations. A summary of these synthetic extreme events can be seen in Table 4. Additionally, synthetic gauges have been placed to monitor key locations around Key West. The comparison plots for these synthetic gauges are shown in figures 4-7. Each synthetic mega-tsunami source consists of 20 unit sources, covering a rupture area of 1000 km by 100 km. Mega-tsunami synthetic sources are magnitude of 9.3 Mw events generated in each Atlantic subduction zone. The purpose of this analysis is to confirm the stability of the Forecast model under inundation from mega-events in all possible directions and to determine an upper bound for potential inundation hazard areas. Figures 11-18 plot Forecast model and Reference model comparisons of maximum current speed and maximum wave amplitudes for all synthetic cases listed in table 4. It can be seen that both Reference and Forecast models are stable and have very good agreement throughout the duration of the model runs. The complex bathymetry and network of low-lying islands around Key West have the expected effects of increasing current speeds in narrow or bottlenecked areas. Surprisingly, maximum inundation is caused by the Nicaraguan ATSZ 68-77 event, which produces a maximum 2.63 meter high wave in Key West Township (Figure 14). The computational results show inundation in the low lying areas of Key West and the Naval Air Station airstrip. Minimal wave height was caused by the Caribbean ATSZ38-47 event (Figure 11). Most of this Tsunamis energy is directed toward the Southeast Atlantic and is greatly attenuated by the Caribbean islands prior to reaching Key West.

5 Summary and Conclusion

A tsunami forecast model was developed for the community of Key West, Florida. The developed model is being implemented into NOAAs Short-term Inundation Forecast of Tsunamis (SIFT) to provide real-time modeling forecasts of the tsunami wave characteristics, runup, and inundation along the Key West coastline. Discussion of the details of each individual component of the forecast model, including the bathymetry and topography, the basic model setup, and the model parameters are provided in this report. The forecast model employs grids as fine as 90m can accomplish a 4-hr simulation after tsunami arrival in under 10 minutes of computation time. A reference model was developed using grids as fine as 20 m to provide a referencing results basis for evaluation of forecast model performance. Model validations have been carried out for the Key West Forecast and Reference models using 8 synthetic tsunami events as well as a recreation of the 1755 Lisbon event (see table 2.) The computed results for the Forecast and Reference models showed good agreement with each other, however there does not exist a historical record to corroborate the model results. As additional tidal records become available this model report should be re-visited to confirm the veracity of this report. The maximum C grid wave height recorded after the battery of large magnitude Atlantic subduction zone tsunami tests was 2.63 meters. The resulting maximum inundation occurs in and around the low lying regions of the airport and the Naval Air Station. All model validation and stability tests demonstrated that the Forecast and Reference Tsunami models developed for Key West, FL, are accurate, robust, and efficient for their implementation into both the short-term real-time tsunami forecast system and long-term tsunami inundation investigations.

6 Acknowledgments

The author would like to thank Chris Chamberlain for collaborating on the development of new plotting routines and for his inexhaustible patience, also Yong Wei and Diego Arcas for helpful suggestions and guidance throughout the development of the report.

- Funding source - NOAA & JISAO will be added to each report

- JISAO & PMEL publication #s will be provided

A Figures

(a) Downtown Key West [2]

(b) West coast of Key West [3]

Figure 1: Aerial Approaches to Key West

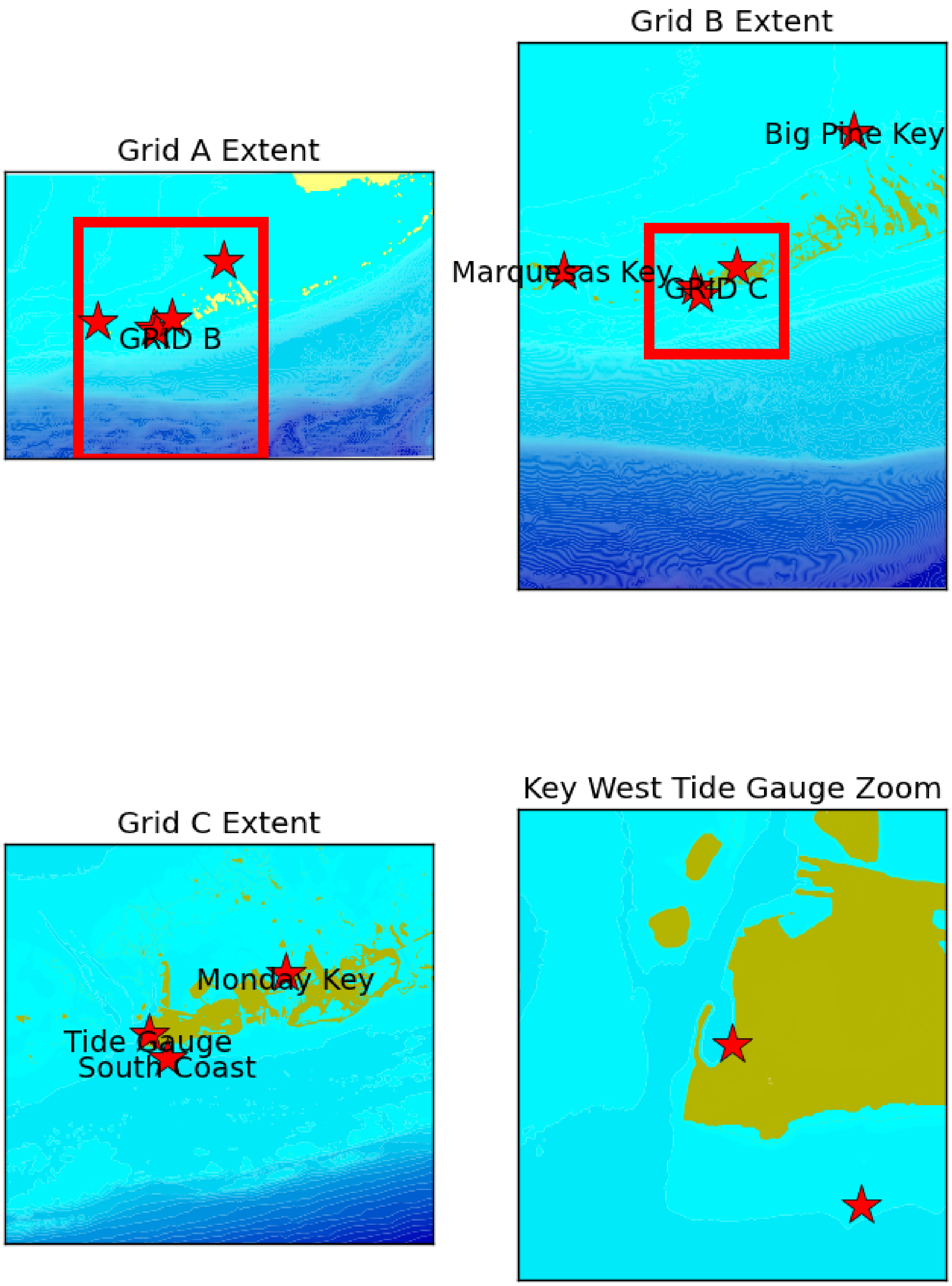

Figure 2: Grid extents and tide gauge locations of Forecast and Reference Models.

Figure 3: Picture of Key West tide station.

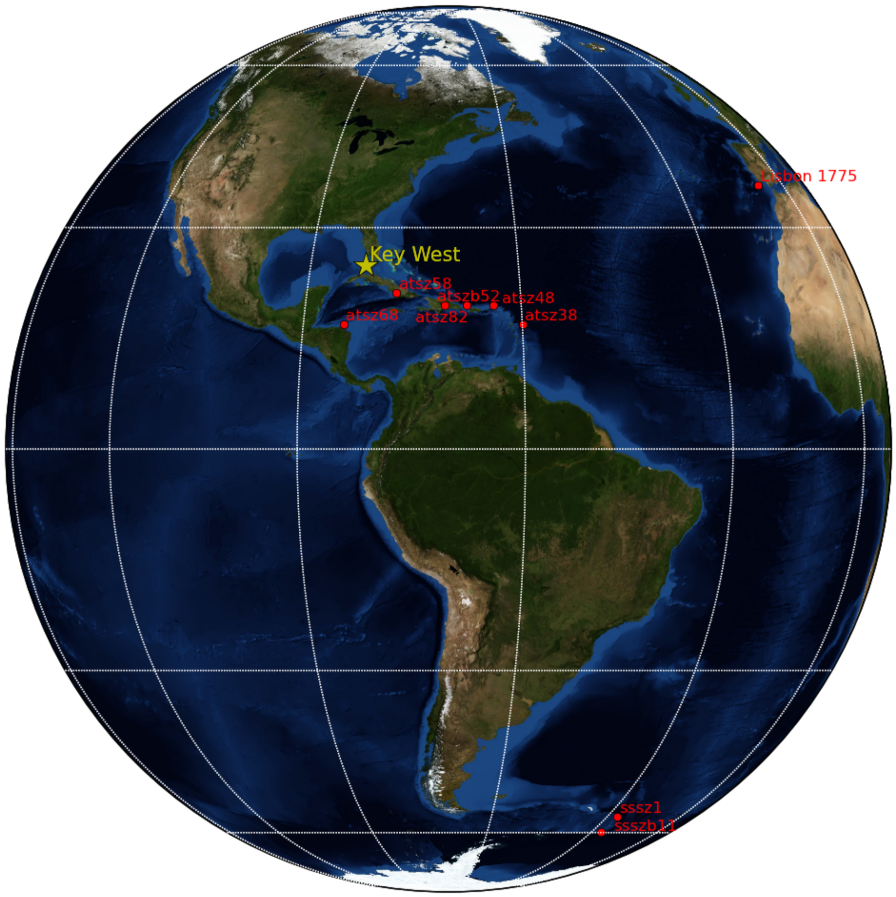

Figure 4: Plot of epicenters of stability and historical tsunami events.

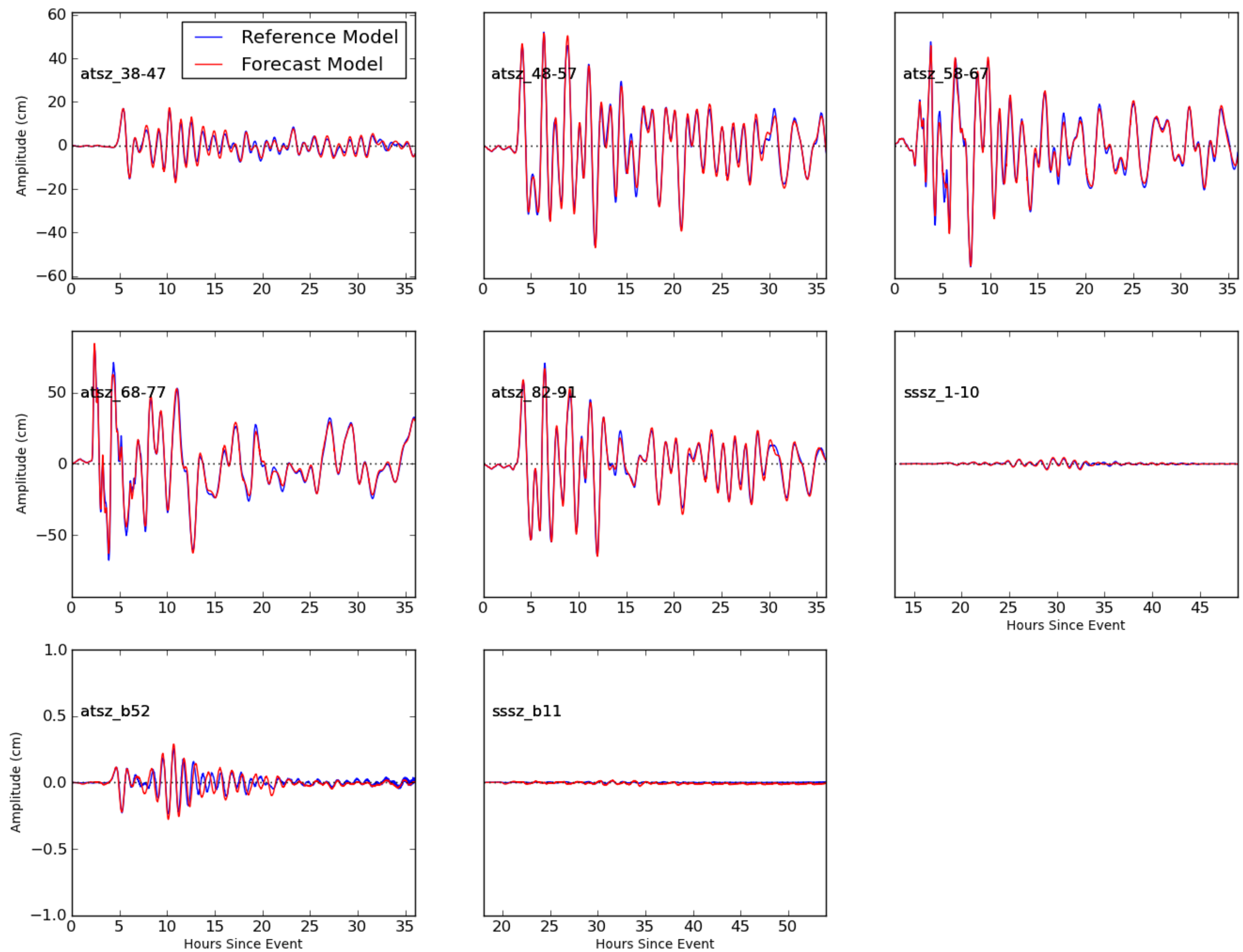

Figure 5: Plot of stability events for Key West tide gauge.

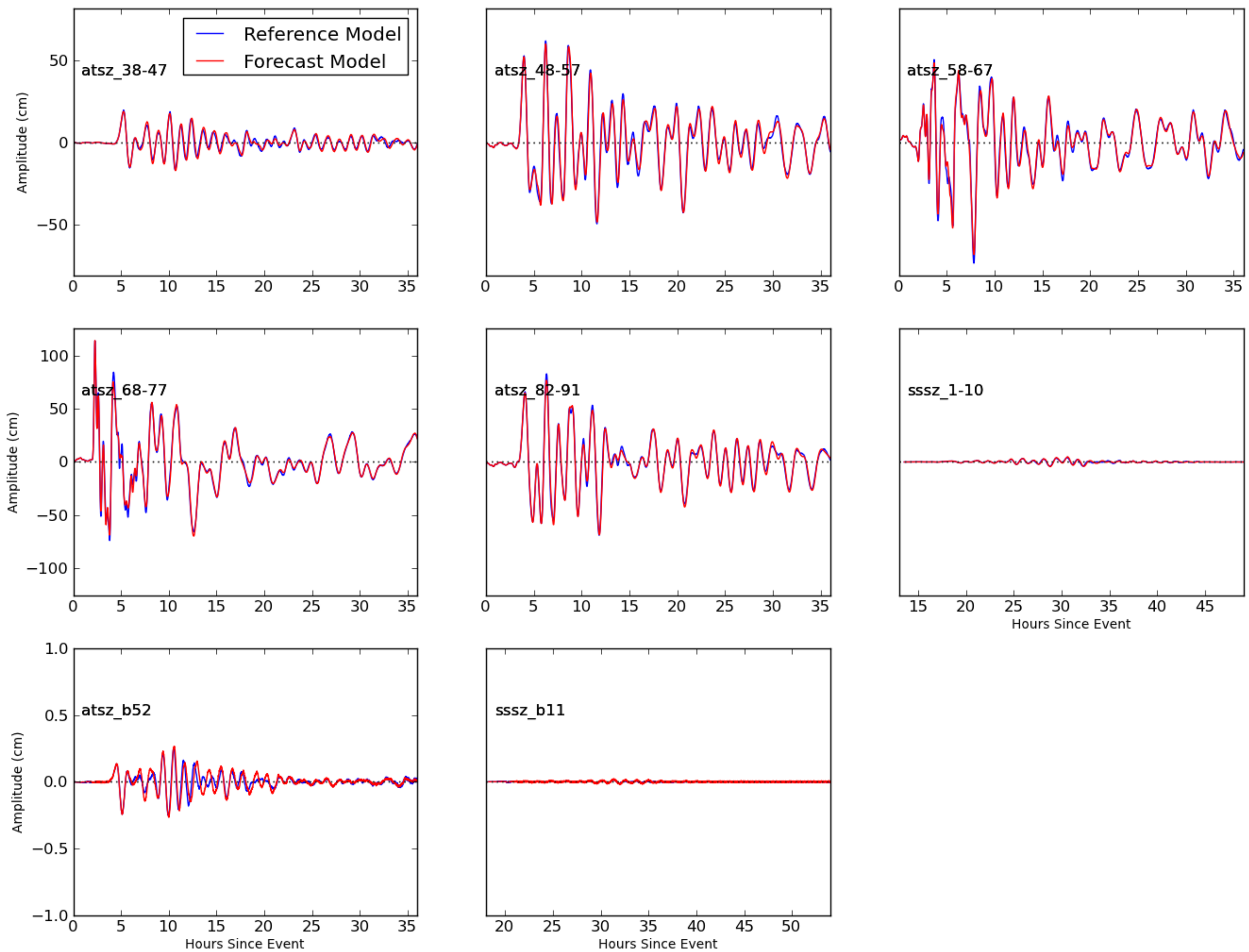

Figure 6: Plot of stability events for South Coast synthetic tide gauge.

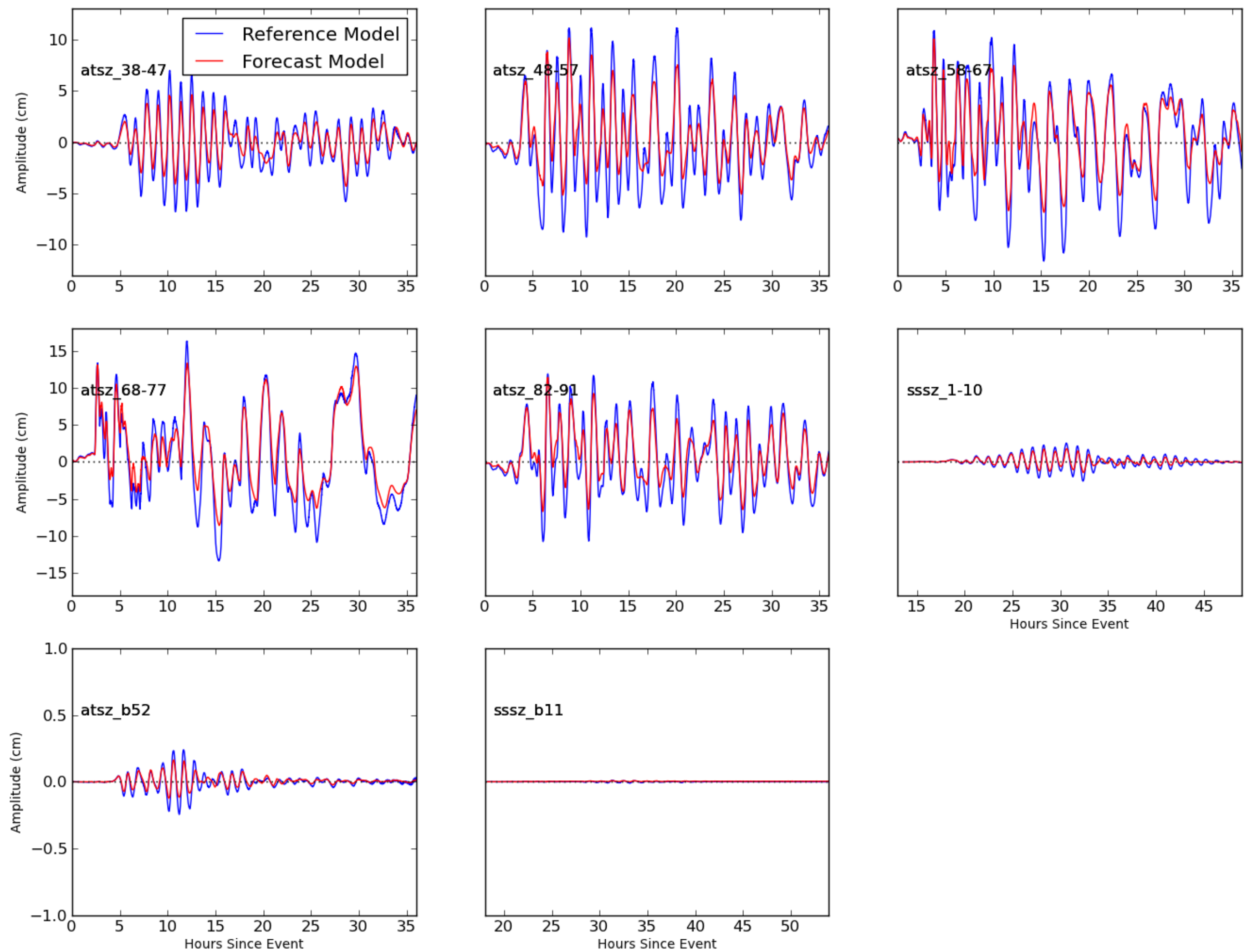

Figure 7: Plot of stability events for Monday Key synthetic tide gauge.

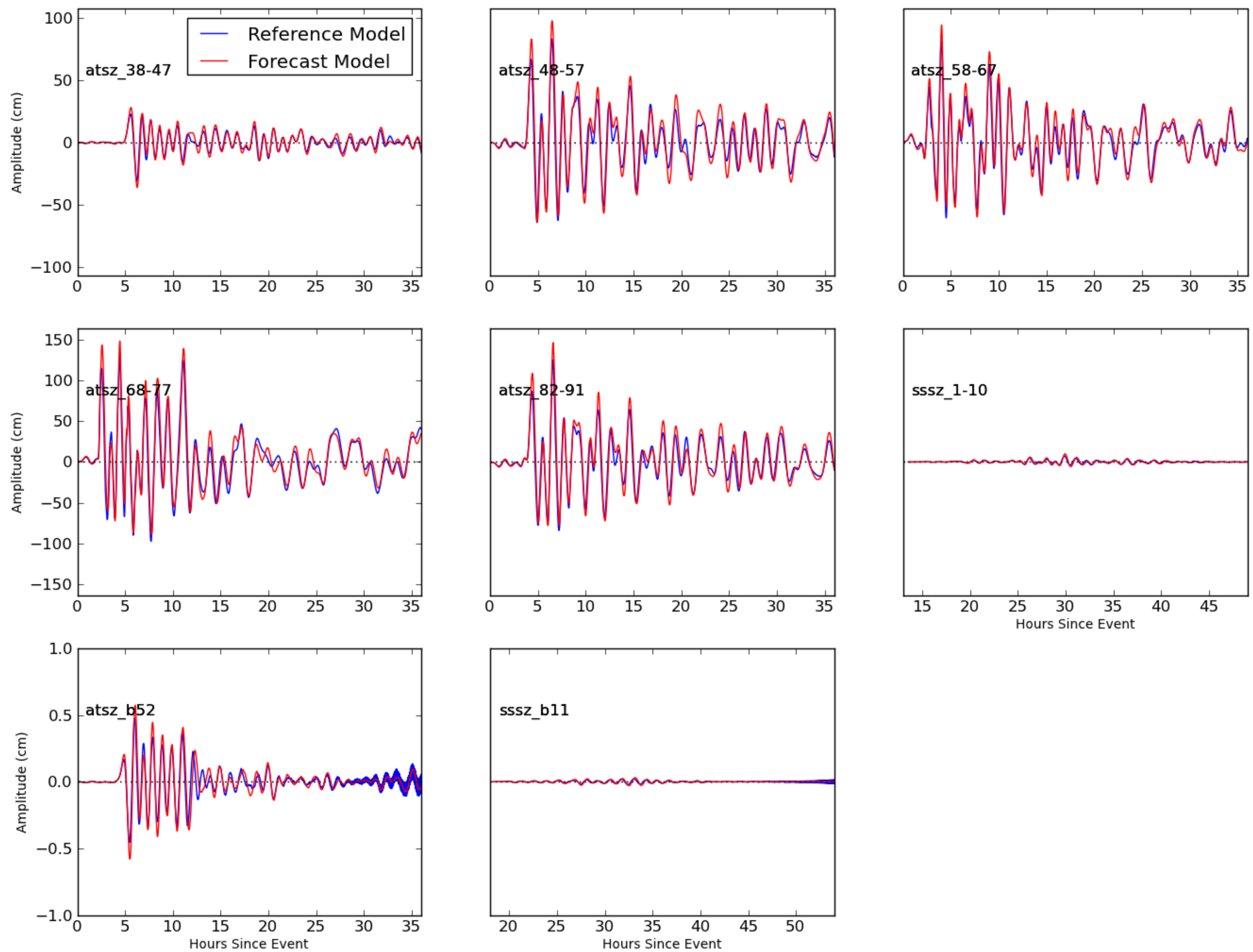

Figure 8: Plot of stability events for Marquesas Key synthetic tide gauge.

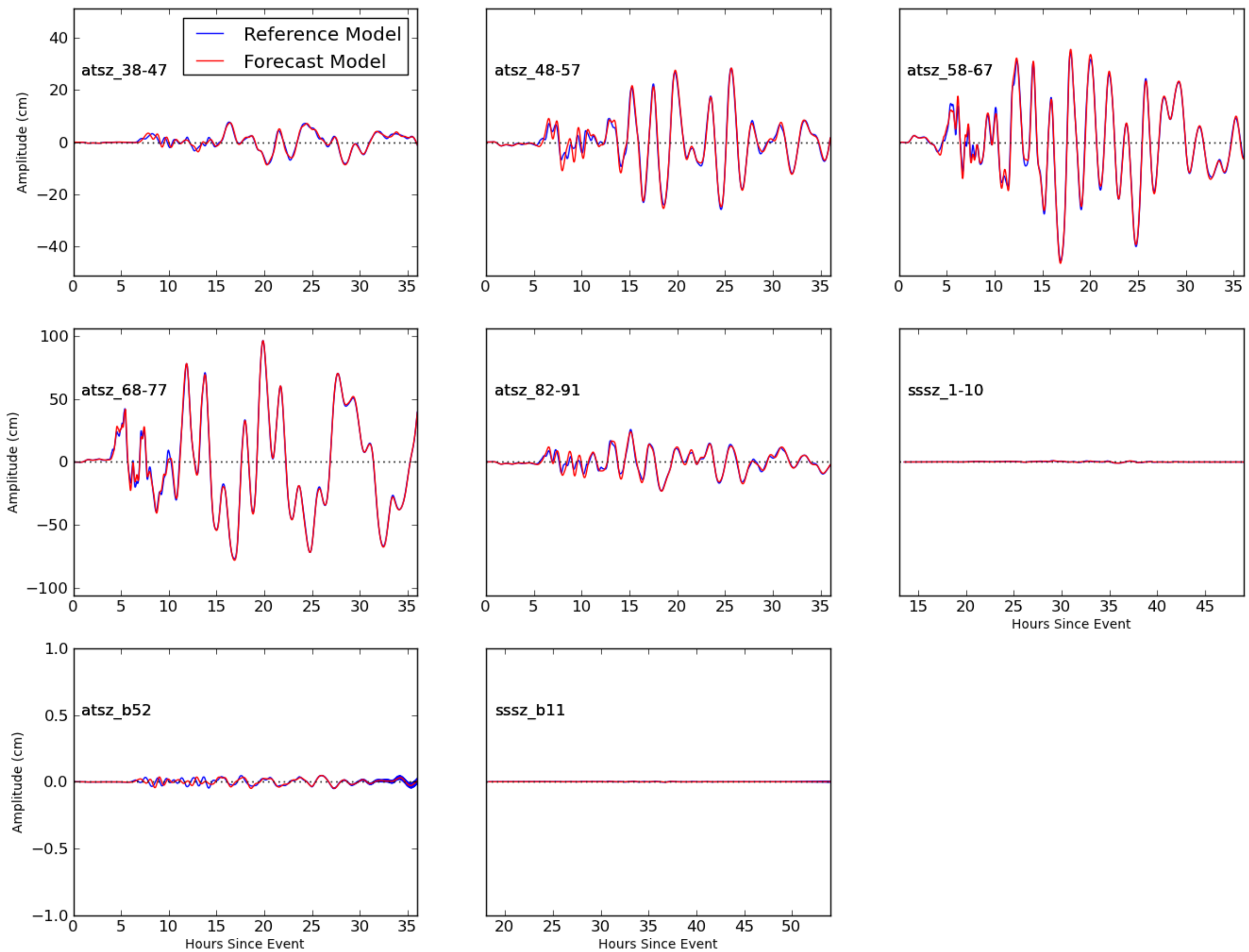

Figure 9: Plot of stability events for Big Pine Key synthetic tide gauge.

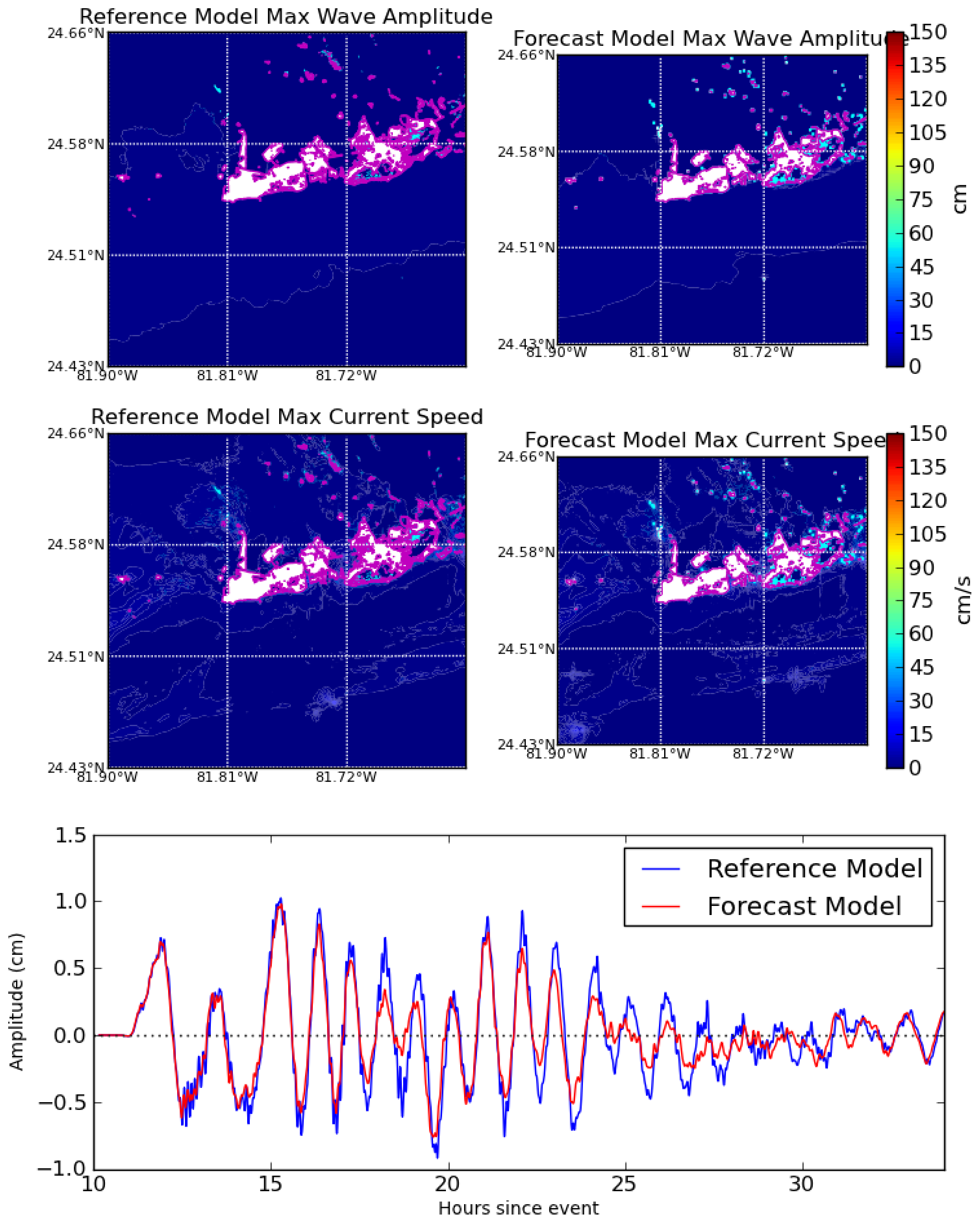

Figure 10: Plot of Forecast and Reference Model Max Current and wave heights for 1775 Lisbon.

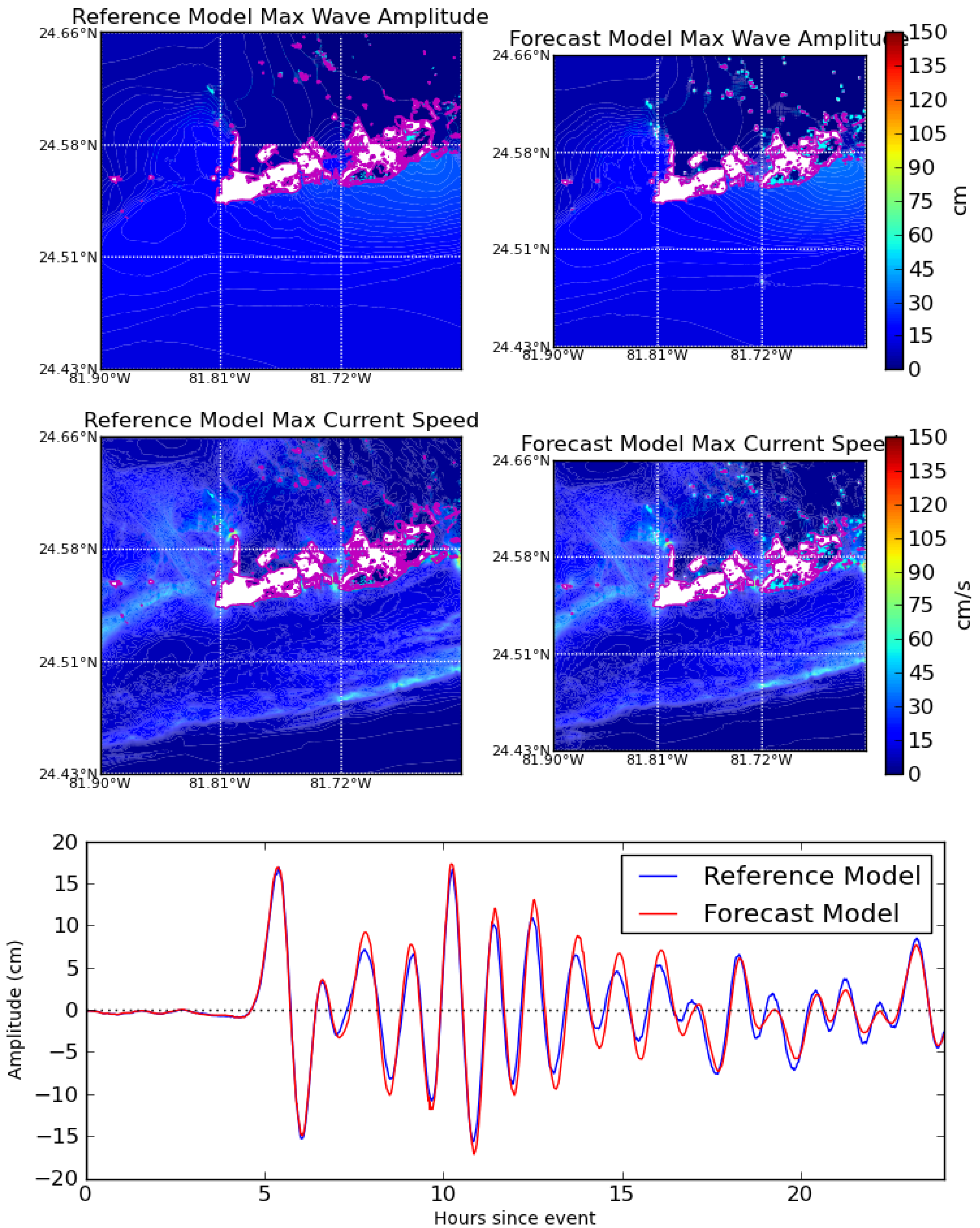

Figure 11: Plot of Forecast and Reference Model Max Current and wave heights for ATSZ 38-47.

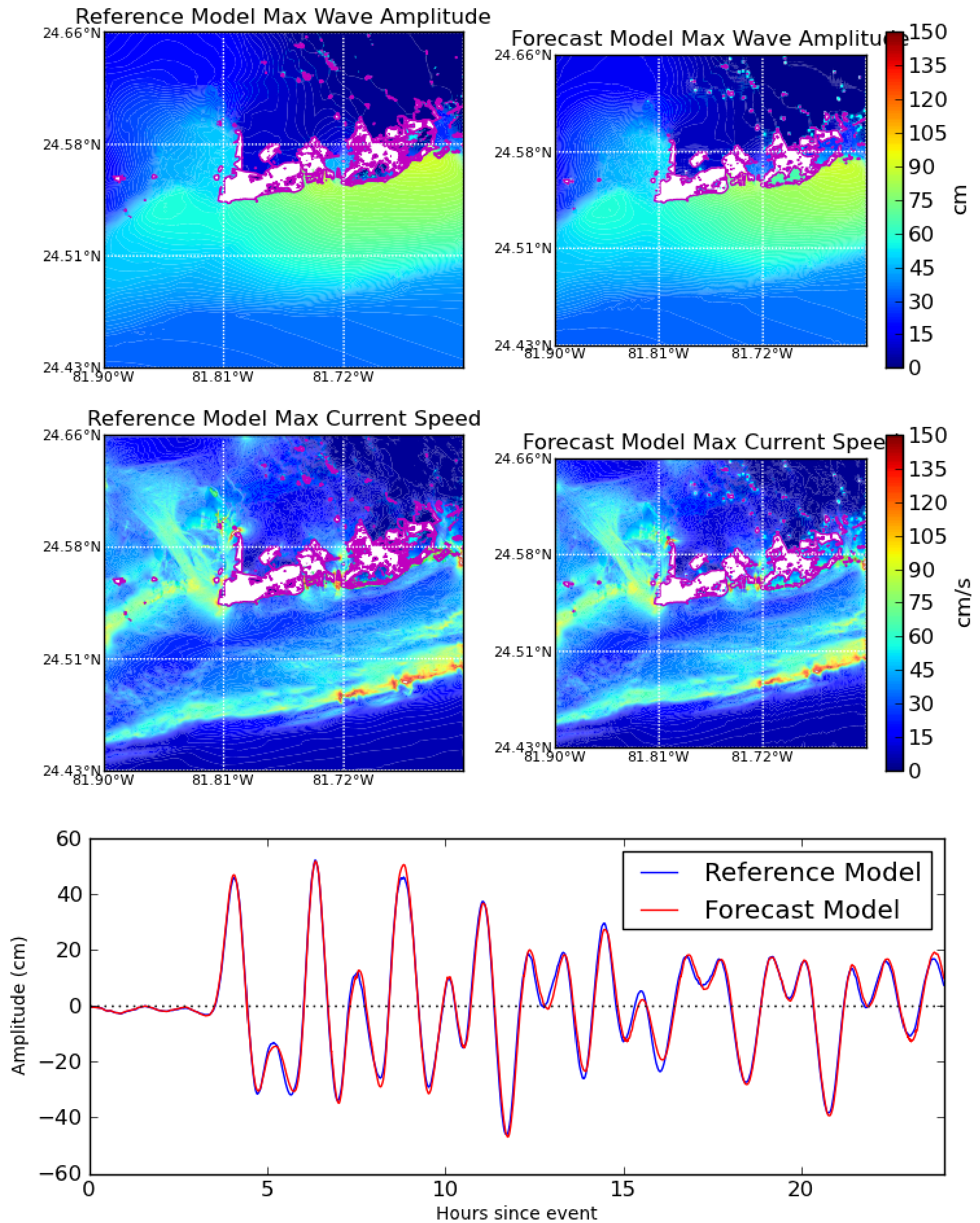

Figure 12: Plot of Forecast and Reference Model Max Current and wave heights for ATSZ 48-57.

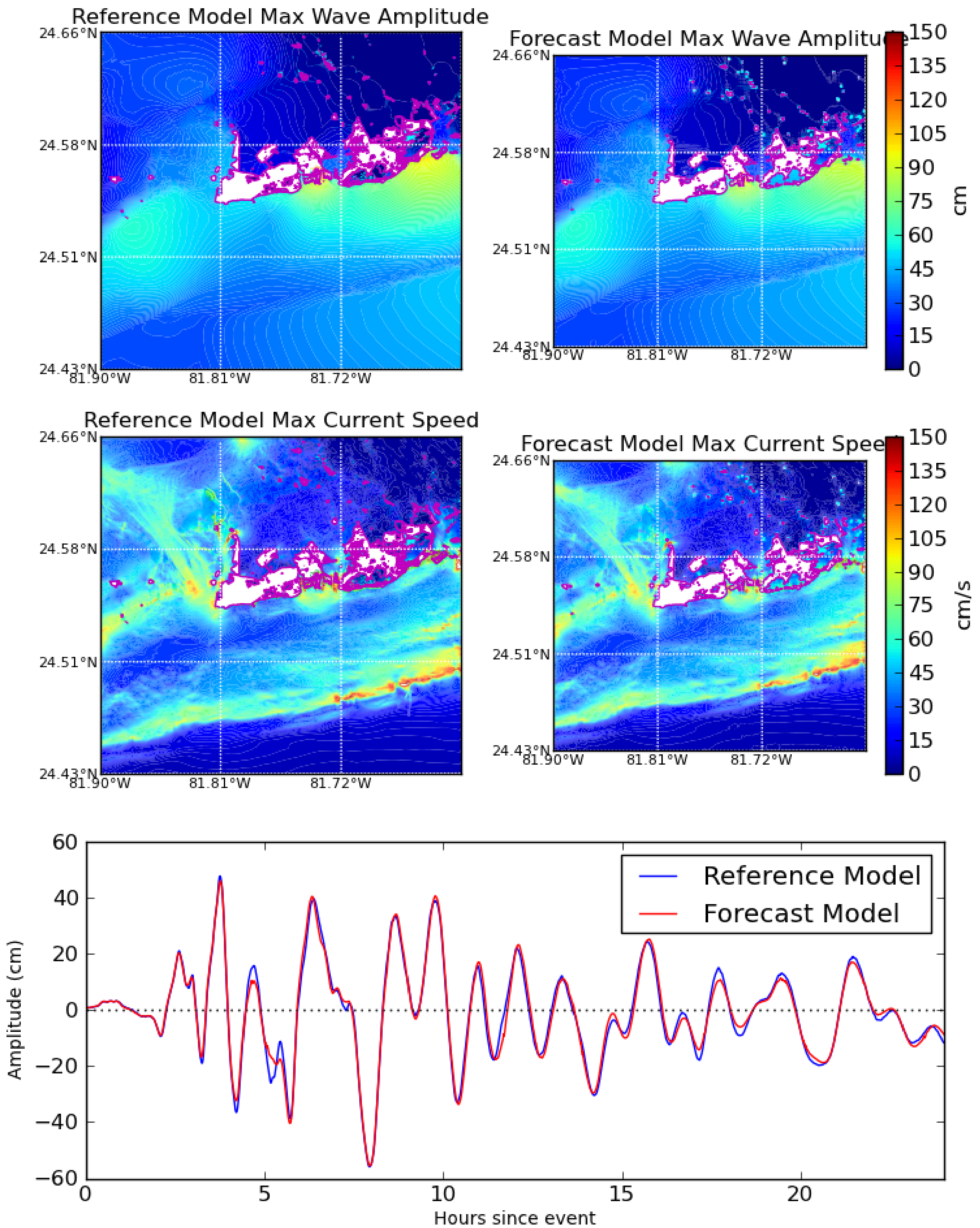

Figure 13: Plot of Forecast and Reference Model Max Current and wave heights for ATSZ 58-67.

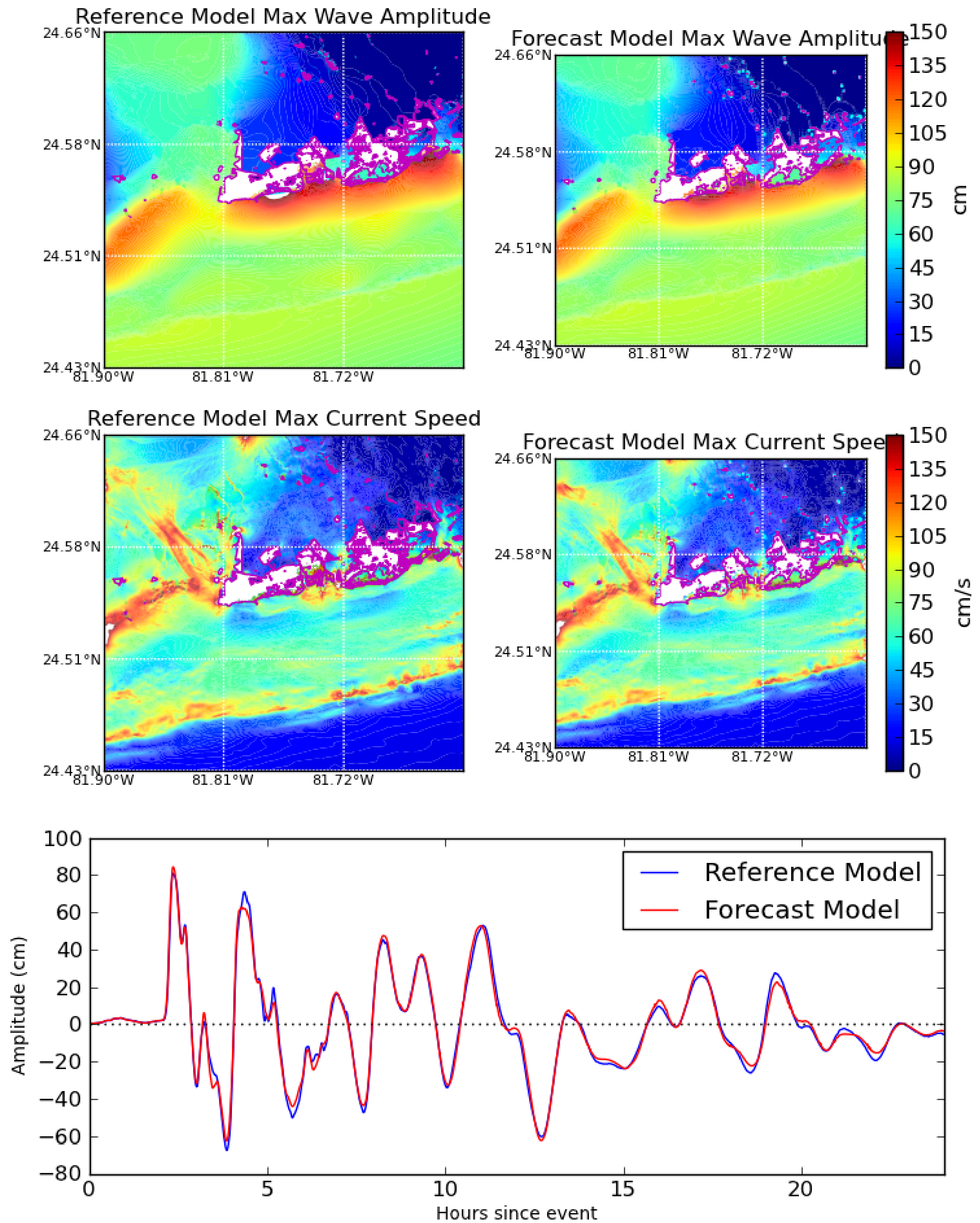

Figure 14: Plot of Forecast and Reference Model Max Current and wave heights for ATSZ 68-77.

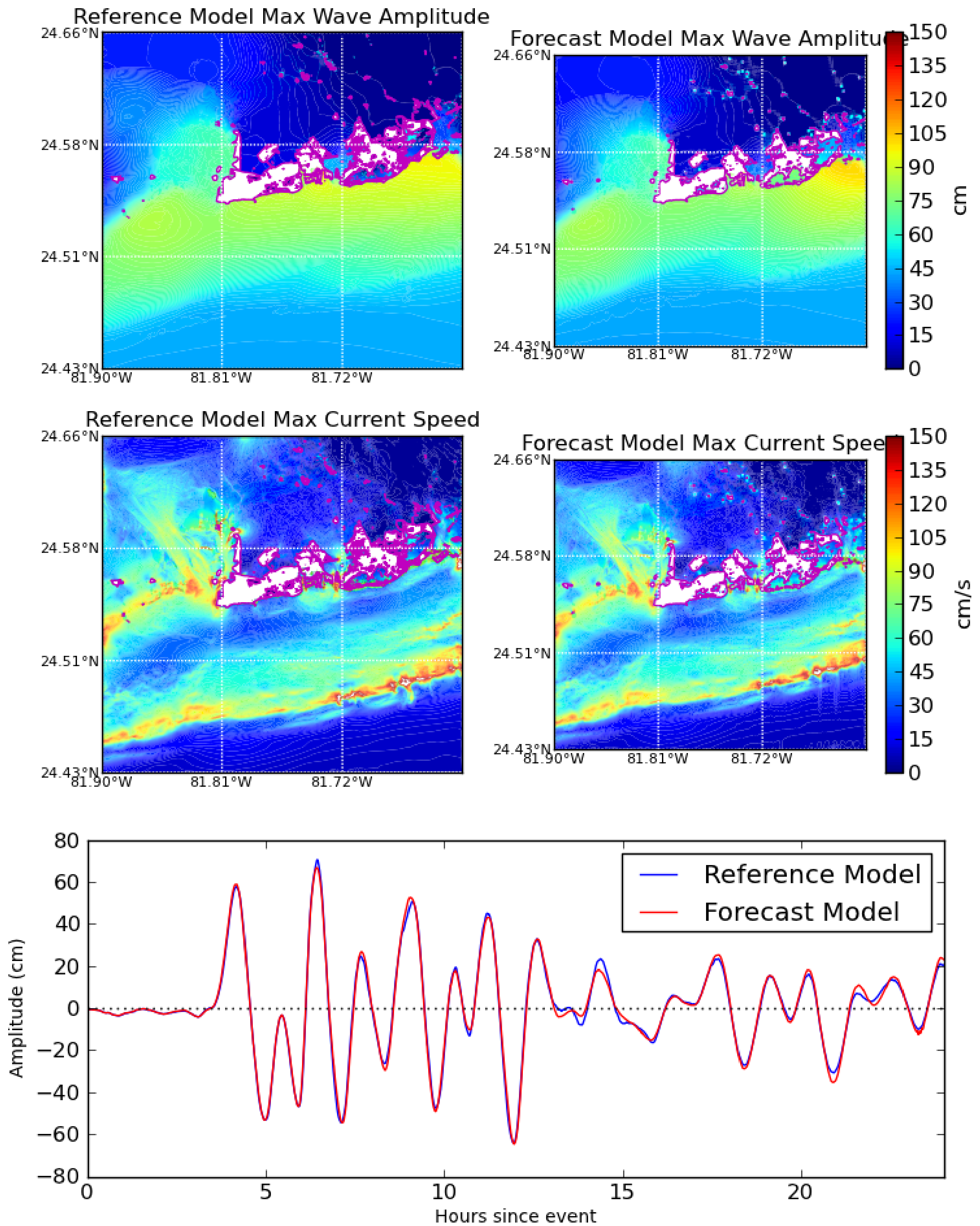

Figure 15: Plot of Forecast and Reference Model Max Current and wave heights for ATSZ 82-91.

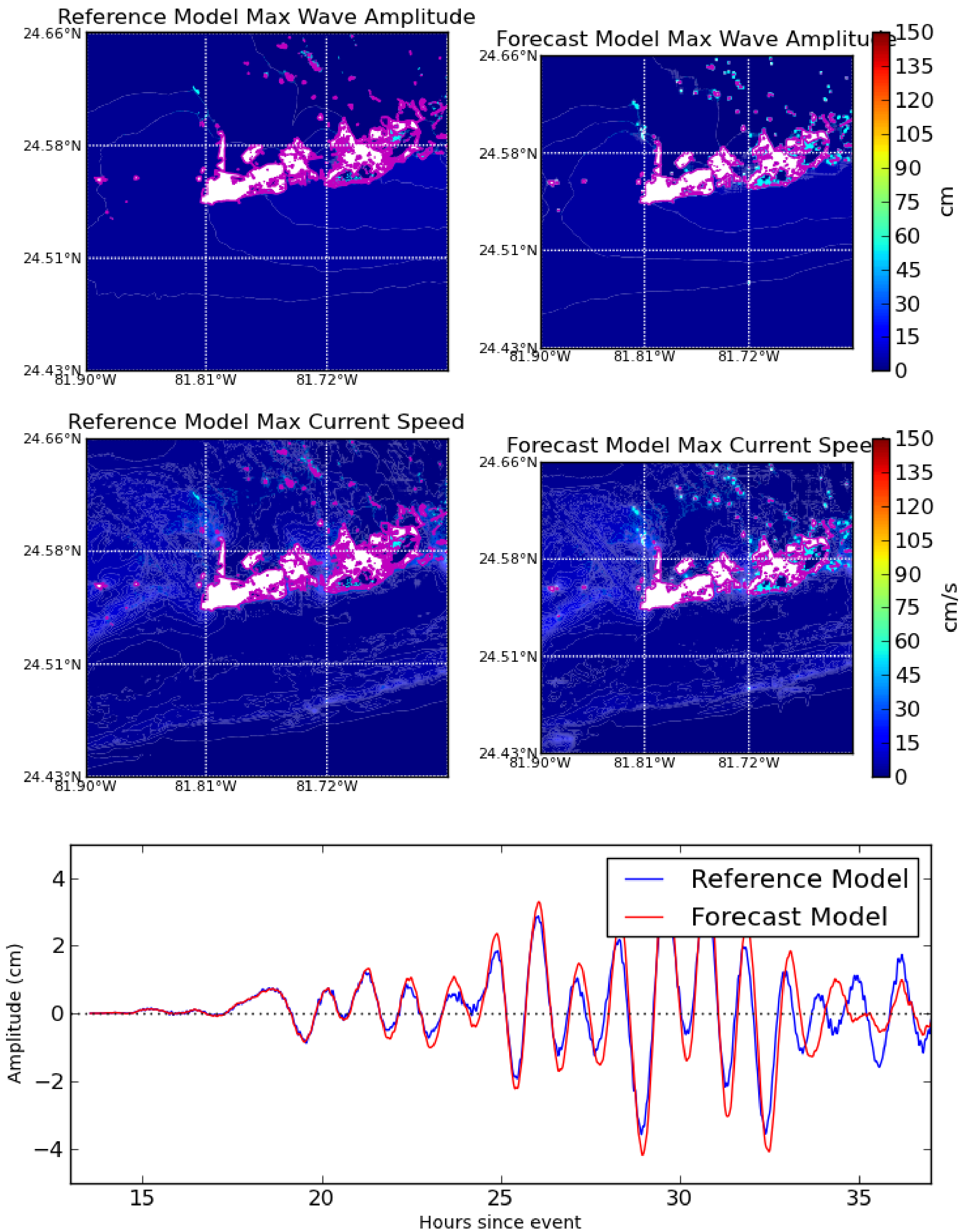

Figure 16: Plot of Forecast and Reference Model Max Current and wave heights for SSSZ 1-10.

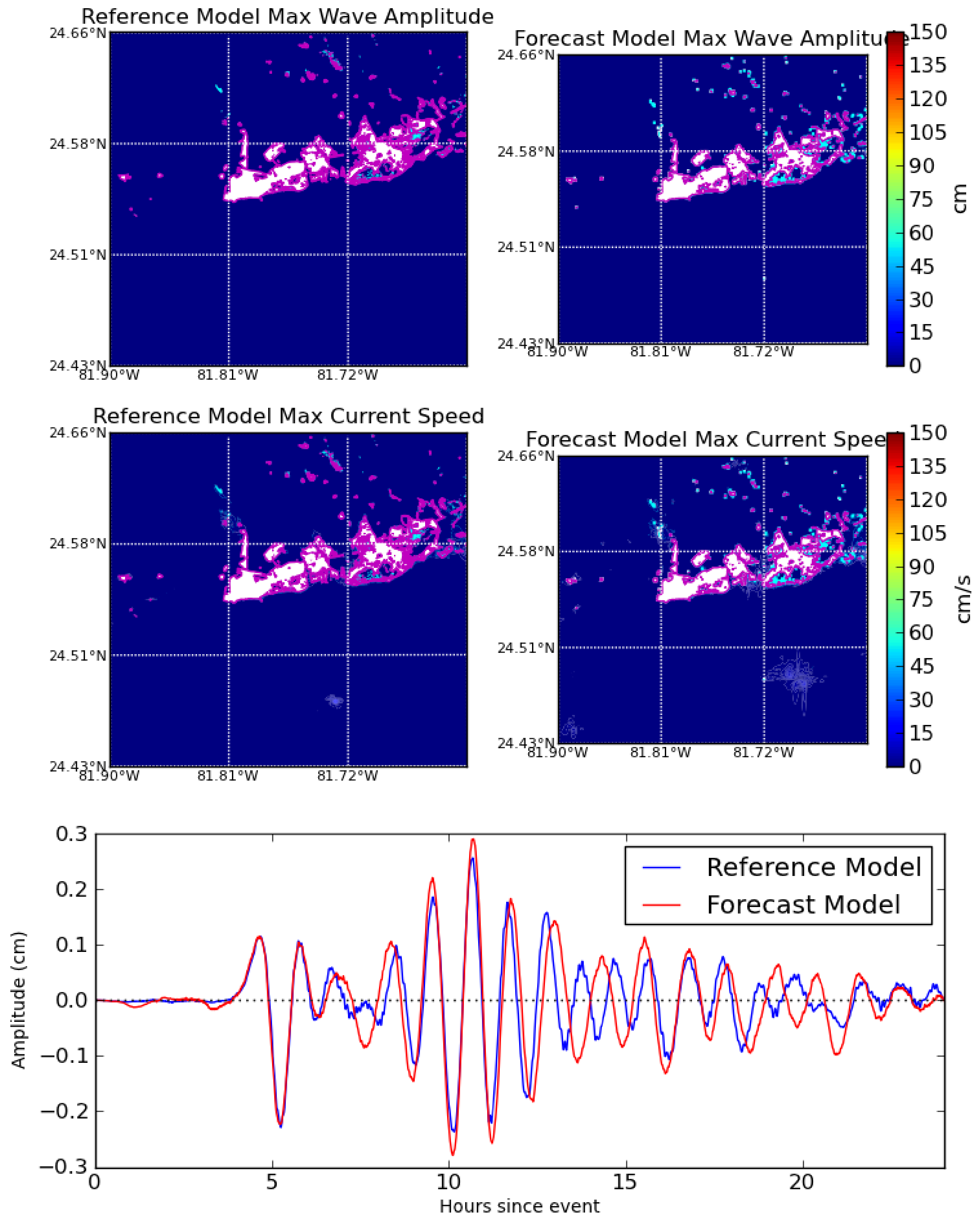

Figure 17: Plot of Forecast and Reference Model Max Current and wave heights for ATSZ B52.

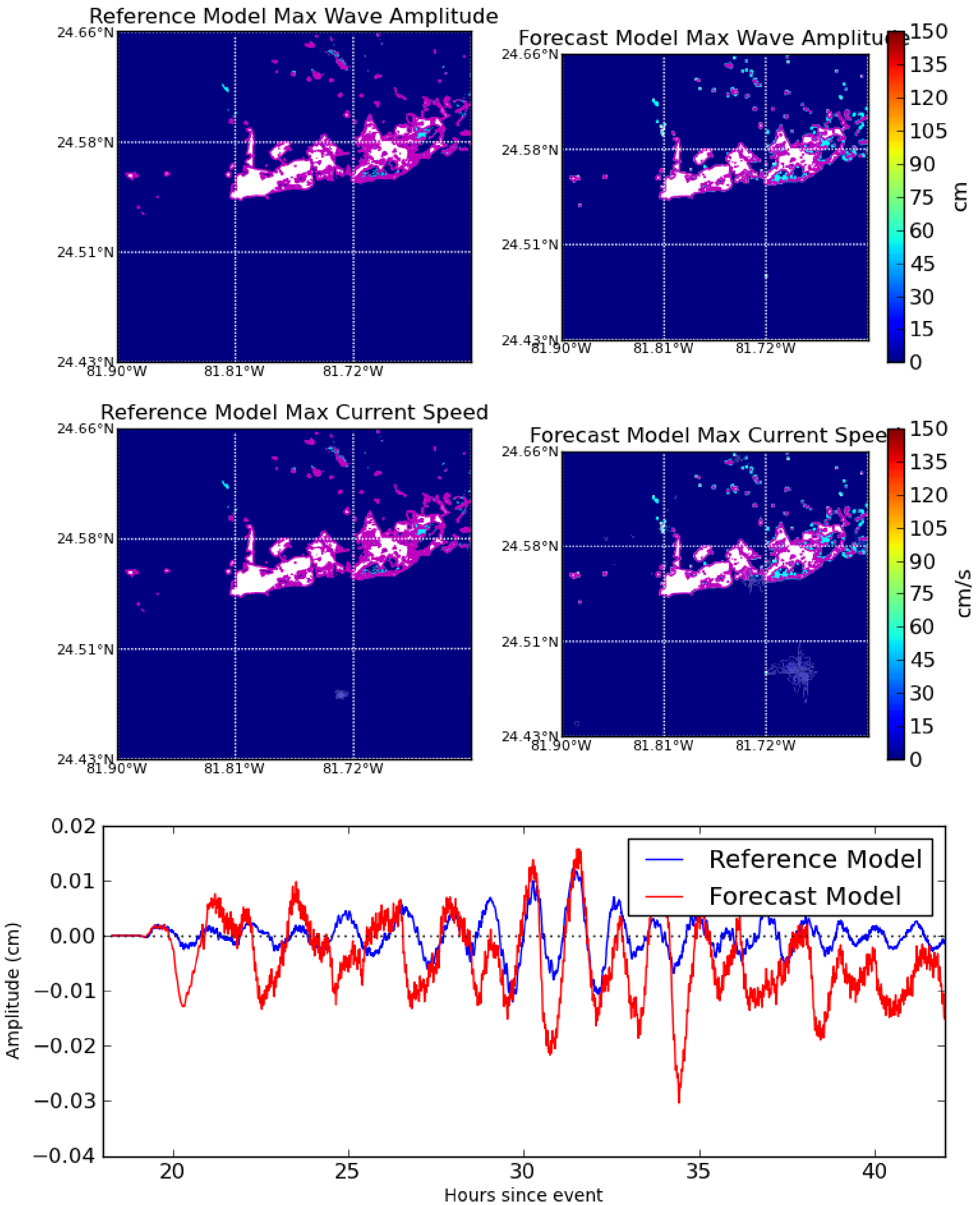

Figure 18: Plot of Forecast and Reference Model Max Current and wave heights for SSSZ B11.

A Tables

Table 1: Location of tide gauge & other modeled areas of interest.

Geographic Location	Grid	Lon	Lat
Key West tide gauge	C	-81.8081	24.552
Southwest Keywest Coast	C	-81.7961	24.5383
Monday Key	C	-81.72	24.588
Marquesas Key	B	-82.071	24.581
Big Pine Key	B	-81.48277	24.8353

Table 2: Table of historical scenarios.

Event	(UTC) Epicenter	Magnitude Mw	Tsunami Magnitude	Tsunami Source
1755 Lisbon	9.40N 36.2W	8.5-9.0	8.5-9.0	hssza1*4.74+hssza2*5.71

Table 3: MOST setup parameters for reference and forecast models for KeyWest, FL.

Grid	Region	Reference Model Coverage Lat. [X] Lon. [X]	Cell Size ["]	nx x ny	Time Step [sec]	Forecast Model Coverage Lat. [X] Lon. [X]	Cell Size ["]	nx x ny	Time Step [sec]
A	Florida Keys	24-25.2 277.5-279.5	27”x30”	241x145	7.85	24-25.2 277.5-279.5	27”x30”	241x145	7.85
B	Marquesas Key to Big Pine Key	24.0-25.0 277.84-278.7	3”x2.7”	1039x1201	0.82	24.0-25.0 277.84-278.7	12”x10.9”	261x301	3.32
C	Key West Township	24.43-24.66 278.1-278.37	0.66”x0.61”	1484x1258	0.5	24.43-24.66 278.1-278.37	3”x2.7”	330x280	2.27
Minimum offshore depth [m]			5				5		
Water depth for dry land [m]			0.1				0.1		
Friction coefficient [n2]			0.0009				0.0009		
CPU time for 4-hr simulation			668.48 min				8.55 min		

Table 4: Table of synthetic mega and micro tsunamis.

Sce. No	Scenario Name	Source Zone	Tsunami Source	a (m)
		Mega-tsunami scenario		
1	ATSZ 38-47	Atlantic	A38-A47, A38-A47	25
2	ATSZ 48-57	Atlantic	A48-A57, B48-B57	25
3	ATSZ 58-67	Atlantic	A58-A67, B58-B67	25
4	ATSZ 68-77	Atlantic	A68-A77, B68-B77	25
5	ATSZ 82-91	Atlantic	A82-A91, B82-B91	25
6	SSSZ 1-10	South Sandwich	A1-A10, B1-B10	25
		Mw 7.5 Scenario		
7	ATSZ B52	Atlantic	B52	1
		Micro-tsunami Scenario		
8	SSSZ B11	South Sandwich	B11	1

A Input Files

A.1 Reference Model .in for Key West, Florida

0.00001	Minimum amplitude of input offshore wave (m)
5.0	Input minimum depth for offshore (m)
0.1	Input ”dry land” depth for inundation (m)
0.0009	Input friction coefficient (n2)
1	A & B grid runup flag (0=disallow, 1=allow runup)
300.0	Blow-up limit (maximum eta before blow-up)
0.48	Input time step (sec)
310000	Input number of steps
15	Compute ”A” arrays every nth time step, n=
1	Compute ”B” arrays every nth time step, n=
60	Input number of steps between snapshots
0	...Starting from
1	...Saving grid every nth node, n=1

A.2 Forecast Model .in for Key West, Florida

0.00001	Minimum amplitude of input offshore wave (m)
5.0	Input minimum depth for offshore (m)
0.1	Input ”dry land” depth for inundation (m)
0.0009	Input friction coefficient (n2)
1	A & B grid runup flag (0=disallow, 1=allow runup)
300.0	Blow-up limit (maximum eta before blow-up)
2.17	Input time step (sec)
70000	Input number of steps
3	Compute ”A” arrays every nth time step, n=
1	Compute ”B” arrays every nth time step, n=
15	Input number of steps between snapshots
0	...Starting from
1	...Saving grid every nth node, n=1

References

[1] *Key west (city) QuickFacts from the US census bureau*, http://quickfacts.census.gov/qfd/states/12/1236550.html.

[2] *Panoramio - photo of key west*, http://www.panoramio.com/photo/32809041.

[3] *Panoramio - untitled photo*, http://www.panoramio.com/photo/5593661.

[4] *SOFIA - paper - geology and hydrogeology of the florida keys*, http://sofia.usgs.gov/publications/papers/keys_geohydro/.

[5] *Tourism data*, http://www.keywestchamber.org/PDF/trends.PDF.

[6] Uri ten Brink, David Twichell, Jason Chaytor1 Homa Lee3 Brian Buczkowski1 Patrick Lynett2, Eric Geist3, and Claudia Flores, *Regional assessment of tsunami potential in the gulf of mexico: U.S. geological survey administrative report.*, Tech. report.

[7] E. Gica, M. Spillane, C.D. Chamberlin V.V. Titov, and J.C. Newman, *Development of the forecast propagation database for NOAA's short-term inundation forecast for tsunamis (SIFT)*, NOAA Tech. Memo. OAR PMEL-139, NTIS: PB2008-109391, 89 pp (2008).

[8] C. E. Synolakis, E. N. Bernard, V. V. Titov, U. Knolu, and F. I. Gonzlez, *Validation and verification of tsunami numerical models*, Pure and Applied Geophysics **165** (2009), no. 11-12, 2197–2228.

[9] C.E. Synolakis, E.N. Bernard, U. Knolu V.V. Titov, and F.I. Gonzlez, *Standards, criteria, and procedures for NOAA evaluation of tsunami numerical models*, NOAA Tech. Memo. OAR PMEL-135, NTIS: PB2007-109601, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 55 pp (2007).

[10] L. Tang, V. Titov, and C.D. Chamberlin, *Development, testing, and applications of site-specific tsunami inundation models for real-time forecasting*, Res., 114, C12025, doi:10.1029/2009JC005476 (2009).

[11] L. Tang, V.V. Titov, H.O. Mofjeld M. Spillane D. Arcas E.N. Bernard C. Chamberlin E. Gica , Y. Wei, and J. Newman, *Tsunami forecast analysis for the may 2006 tonga tsunami*, Res., 113, C12015, doi: 10.1029/2008JC004922 (2008).

[12] V. V Titov, F. I Gonzalez, E. N. Bernard, M. C Eble, H. O Mofjeld, J. C Newman, and A. J Venturato, *Real-time tsunami forecasting: Challenges and solutions*, Natural Hazards **35** (2005), no. 1, 3541.

[13] V. V. Titov, F. I. Gonzalez, and Pacific Marine Environmental Laboratory (US), *Implementation and testing of the method of splitting tsunami (MOST) model*, US Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Pacific Marine Environmental Laboratory, 1997.

[14] V. V Titov, F. I Gonzlez, H. O Mofjeld, and A. J Venturato, *NOAA time seattle tsunami mapping project: procedures, data sources, and products*, US Department of Commerce, National Oceanic and Atmospheric Administration, Oceanic and Atmospheric Research Laboratories, Pacific Marine Environmental Laboratory, 2003.

[15] V.V. Titov, *Tsunami forecasting*, Chapter 12 in The Sea, Volume 15: Tsunamis, Harvard University Press, Cambridge, MA and London, England, 371400 (2009).

[16] Y. Wei, Bernard E., V. Titov C. Moore M. Spillane M. Hopkins L. Tang, R. Weiss, and U. Knolu, *Real-time experimental forecast of the peruvian tsunami of august 2007 for U.S. coastlines*, Geophys. Res. Lett., 35, L04609, doi: 10.1029/2007GL032250 (2008).